A RESUMÉ OF THE VARIOUS METHODS EMPLOYED FOR THE DETERMINATION OF e/m FOR THE ELECTRON

BY

CHARNJIT SINGH

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY CHARNJIT SINGH

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Chas. T. Knipp
In Charge of Thesis

A. P. Carman
Head of Department

Recommendation concurred in*

Committee
on
Final Examination*

*Required for doctor's degree but not for master's

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I. HISTORICAL SKETCH

The word "electron" was first suggested in 1891 by Dr. G. Johnson Stoney as a name for the natural unit of electricity: namely, that quantity of electricity which must pass through a solution in order to liberate at one of the electrodes one atom of hydrogen or one atom of any equivalent substance. The word "electron" was introduced to denote simply a definite elementary quantity of electricity without any reference to the mass or inertia which may be associated with it. Professor Stoney implies that every atom must contain at least two electrons; one positive and one negative, because otherwise, it would be impossible that the atom as a whole be electrically neutral.

It is obvious that a word is needed which denotes merely the elementary unit of electricity and has no implications as to where that unit is found, to what it is attached, with what inertia it is associated, or whether it is positive or negative in sign; and it is also apparent that the word "electron" is the logical one to associate with this conception. J.J. Thomson's word corpuscle is a very appropriate one to denote the very minute inertia with which the negative electron is found associated in cathode rays.

With the discovery, due to use of the new agency, X rays, the atom as an ultimate indivisible thing was gone, and the era of the constituency of the atom began. And with the astonishing rapidity during the past twenty five years the properties of the subatomic world has been revealed.

Physicists began at once to ask diligently and to find at least partial answers to questions like these:

1. What are the masses of the constituents of the atoms torn

asunder by X rays and similar agencies?

2. What are the values of the charges carried by these constituents?
3. How many of these constituents are there?
4. How large are they, i.e., what volume do they occupy?
5. What are their relations to the emission and absorption of light and heat waves, i.e., of electromagnetic radiation?
6. Do all atoms possess similar constituents? In other words, is there a premordial sub-atom out of which atoms are made?

The partial answer to the first of these questions came with the study of the electrical behavior of rarefied gases in so-called vacuum tubes. Sir J.J. Thomson and Wiechert showed independently in 1897 that the value of e/m for the negative ion in such exhausted tubes is about 1.8×10^7 electromagnetic units, or, about 1800 times the value of e/m for hydrogen ion in solution. Since the approximate equality of ne (n is the number of molecules per cu.cm.) in gases and solution meant that e was at least of the same order in both, the only possible conclusion was that the negative ion which appears in discharges in exhausted tubes has a mass, i.e., an inertia only 1/1800th of the mass of the lightest known atom, namely, the atom of hydrogen.

Furthermore, these and other experiments have shown that e/m for the negative carrier is always the same whatever be the nature of the residual gas in the discharge tube. This was an indication of an affirmative answer to the sixth question above, an indication which was strengthened by Zeeman's discovery in 1897 of the splitting by a negative field of a single spectral line into two or three lines, for this when worked out quantitatively, pointed to the

existence within the atom of a negatively charged particle which had approximately the same value of e/m. Attempts had been first made at a direct determination of e by Townsend in 1897, and was followed by J.J. Thomson, H.A. Wilson, Bogeman and Millikan. The latter applied a number of methods: One of them being the method of observation. His results are given below in the table. The table is taken from Millikan's book entitled "The Electron":-

Series	Charge	Value of e	Weight assigned
1	3e	4.59	7
2	4e	4.56	7
3	2e	4.64	6
4	5e	4.83	4
5	2e	4.87	1
6	6e	4.69	3

The study of e/m for positive ions in exhausted tubes though first carried out quantitatively by Wien has been elaborately and most successfully dealt with by Sir J.J. Thomson. The results of the works of all observers up to date seem to show quite conclusively that e/m for a positive ion in gases is never larger than its value for the hydrogen ion in electrolysis, and that it varies with different sorts of residual gases just as it is found to be in electrolysis.

II. DETERMINATION OF e/m

General Theory.- Different methods have been used to determine the ratio e/m for small particles, but most of the calculations depend on some experimental investigations of the effect of a magnetic force on the motion of the particle. The simplest case is that of a particle moving in a vacuum in which the electric force is

zero and the magnetic force H is perpendicular to the direction of the motion. If v be the velocity of the particle, the force Hev acting on it is in a direction at right angles to the direction of the motion and to the magnetic force, so that when H is constant the particle moves in a circle with a constant velocity. The radius r of the circle is obtained by equating the centrifugal force to the force Hev along the normal to the trajectory. Hence:

$$mv^2/r = Hev$$

or

$$e/m = v^2/rHv = v/rH.$$

In a discharge tube containing a gas at a very low pressure the electric force in the neighborhood of the cathode is large, so that the particles set free from the cathode acquire a high velocity and may penetrate considerable distances without much loss of energy by collision with molecules. If the electrodes are fixed at one end of the tube, the rays move with a velocity which is approximately constant for the remainder of their path, and the curvature 1/r of their trajectory produced by a magnetic force may easily be found, so that one relation between the two quantities e/m and v is thus obtained. If in addition the velocity v is known, or some other relation connecting e/m and v, the values of both of these quantities may be obtained.

In 1890 Schuster read a paper before the Royal Society in which he mentioned that an upper limit and a lower limit for the ratio e/m could be established.

He mentioned that particles are projected from the cathode. The observed effect of the magnet on them is exactly what it should be under the circumstances. The path of the particles can be traced by means of the luminosity produced by the molecular impacts. If

the trajectory is originally straight, it bends under the influence of a magnet. The curvature of the rays depends on two unknown quantities, the velocity of the particles and the quantity of electricity they carry.

If the particles carrying a charge are moving with velocity at right angles to the lines of force, the radius of curvature r is determined by the equation

$$mv^2/r = Hve$$

or
$$e/m = v/Hr, \tag{1}$$

where m is the mass of the particle, and H the magnetic force. If the particles originally at rest start from the cathode at which the potential is taken as zero, and arrive without loss of energy, at a place where the potential is E, we should have another equation, namely

$$2Ee = mv^2. \tag{2}$$

Eliminating v, we find

$$e/m = 2E/H^2r^2. \tag{3}$$

A lower limit, he mentioned, can be calculated as follows: As long as the effect of the magnet on the particles projected from the cathode shows any directional preponderence, we may take it that the velocities of the particles must be greater than the mean velocity in their normal state. For it is clear that, if distribution of velocities was symmetrical in all directions, the magnet would have equal and opposite effects on the charges which move in opposite directions; and if by mutual impact the velocity is reduced to its normal value, it will also have lost any directional inequality. We may obtain a lower limit for e/m if in equation (1) we calculate

$$e/m = v/Hr \tag{4}$$

by putting for r the smallest radius of curvature which can with certainty be traced in the glow, and for v the mean velocity of the particle, according to the kinetic energy of gases.

In an actual experiment by Schuster, H was 200 gausses; r diminished with increasing distance from the cathode. The greatest value which could with certainty be measured was about 1 cm. E was 225 volts at the same place. Taking these numbers we get for the upper limit

$$e/m < 11 \times 10^5$$

and the lower limit he got to be

$$e/m > 10^3.$$

This lower limit for e/m as Schuster found, were very near the observed values.

Wiechert Method.- Wiechert, in January, 1897, first showed that the ratio e/m for a cathode-ray particle is between 4000 and 2000 times as great as the value of e/m corresponding to an atom of hydrogen, the velocity of the cathode being in some cases about one-tenth of the velocity of light. He attributed the large value of e/m to the smallness of the mass m and considered the charges e and E to be the same.

Wiechert, working with rays in hydrogen at a very low pressure, measured the curvature 1/r of the trajectory produced by a known negative force H, and obtained the value of Hv for substitution in the formula

$$e/m = v/Hr.$$

The velocity v was determined by a direct method in which the period of oscillation of a condenser, discharging through a circuit of known self-inductance was used to estimate the short interval

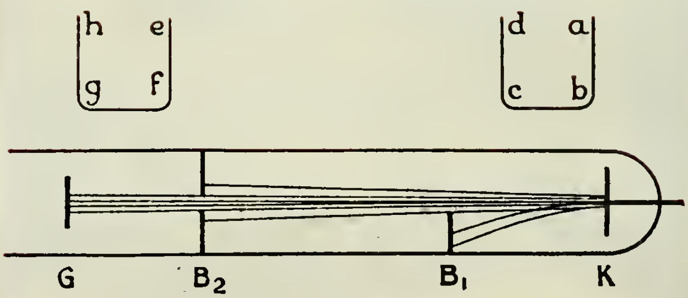


Figure 1.

of time required by the rays to traverse a given distance in the discharge tube. This principle had previously been used by des Condres who found that the cathode rays had a velocity exceeding 2×10^8 centimeters per second. Guided by this result Wiechert designed an apparatus by means of which it was possible to compare the time in which the rays traversed a distance of about 20 centimeters with the period of T of a condenser, T being between 10^{-8} and 10^{-7} second. The arrangement of apparatus is shown by the illustration of the discharge tube (Fig.1). In front of the cathode, K, and at a distance 25 centimeters from it, he placed a plate of glass, G, that fluoresced brightly under the action of the rays. Two metal screens, B_1 and B_2, were placed between the cathode and the glass plate. The screen, B_2, was 5 centimeters from the glass plate and had a slit in the centre a few millimeters wide. The other screen, B_1, 7-1/2 centimeters from the cathode extended across the lower part of the tube, and its edge was parallel to the slit in B_2. The positive electrode, which is not shown in the figure, was in the form of a ring and was placed between the cathode and screen B_1. The discharge was produced by the secondary circuit of a Tesla transformer, and the rays from the center of the cathode, passed over the edge of the first screen and through the slit in the second. A narrow flucrescent strip, a few millimeters wide, marked the points on the surface of glass, G, on which the rays impinged.

When a magnet was placed in a suitable position near the cathode most of the rays bent down and fell on the screen B_1, and only a slight fluorescence was seen on the glass plate.

The two wires, abcd, and efgh, formed part of the circuit of the oscillatory discharge of a condenser, which was charged

inductively by the Tesla apparatus used to produce the cathode rays. Thus, a current flowed through the wires abcd and at the same instant the high potential was established between the electrodes. When the wire is brought close to the tube, as shown in the figure, the magnetic force due to the current in bc counteracts the effect of the magnet, when the cathode rays are emitted, so that some of the rays pass over the edge of B_1. An increase is thus produced in the fluorescence at G, due to the rays which between K and B_1, when the alternating current in the condenser circuit is in a certain phase.

The effect of the current on the rays as they pass from the slit in B_2 to the glass plate is then observed by bringing the wire efgh near the tube. Let t be the time in which the rays travel from B_1 to G, T the period of oscillation of the condenser discharge; then if T is large as compared with t, the deflection produced by the current in fg is in the same direction as the deflection produced by bc. If the period of the condenser discharge is reduced until $T/4 = t$, the deflection produced between B_2 and G becomes very small. Thus, by observing the displacement of the fluorescence of the glass plate obtained by reducing the period, T, the time, t, may be estimated.

It was thus found that for rays for which the value of Hr was 150, the velocity v was about 3×10^9 centimeters per second; and the value e/m about 2×10^7, the true value being possibly greater than these numbers.

Weichert also considered the possibility of determining e/m from measurement of the potential difference, W, between the electrodes. An upper limit of the velocity of the electron in the tube may be obtained on the hypothesis that the rays start from the

negative electrode and move freely under the electric force. The maximum kinetic energy acquired by the charged particle is then,

$$mv^2/2 = eW,$$

and e/m is given by the equation

$$e/m = v^2/2W.$$

The upper limit of the value of e/m thus obtained was 4×10^7.

Subsequently, the arrangement of the apparatus for measuring the velocity of the rays was made; the most probable values of e/m were found to be between

4.64×10^{17} and 3.04×10^{17} in electrostatic units

and 1.55×10^7 and 1.01×10^7 in electromagnetic units.

Kaufman's Method.- Kaufman performed a number of experiments in 1897, on the determination of e/m for cathode rays. He introduced a method by which the deflection due to electric and magnetic force takes place simultaneously and can be measured with great accuracy. His method depends on the simple principle that in a gas at sufficiently low pressures the kinetic energy acquired by the electrons in passing from the cathode to the anode is eW, W being the potential difference between the electrodes. Under these conditions, the value of e/m is given by the formula

$$e/m = 2W/H^2r^2,$$

r being the radius of curvature of the trajectory in a transverse magnetic field H. This implies that the loss of energy of the electrons due to collisions is very small, and the investigations show that any such effect must have been negligible. Kaufman made a number of experiments in which the gas was at different small pressures, and the potential difference between the electrodes required to produce the discharges varied from 3000 to 4000 volts. The

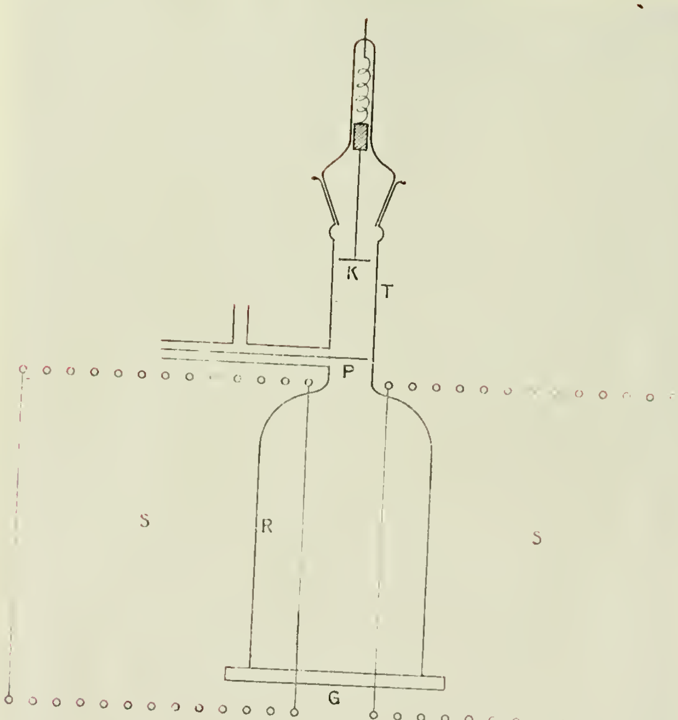


Figure 2.

velocity was liable to be diminished appreciably due to the collision between the rays and molecules, so if W diminishes error in the formulae would increase. But it was observed that there was no appreciable difference in the value of quantity W/H^2r^2 for different pressures at which the experiments were performed. So that if we take eW as the kinetic energy the error would not be serious.

The apparatus that Kaufman used is shown in Fig.2. The glass tube, R, 11 centimeters long and 6.5 centimeters wide, was closed with a gas plate, G, the electrodes K and P being contained in the tube T. The cathode K was raised to a high potential by a Wimshurst machine, and the potential difference W between the electrodes was measured by an electrostatic voltmeter. The case of the voltmeter and the positive electrode P were connected to earth. A thin layer of chalk, which fluoresced under the action of the rays, was spread over the plate G, an electrode which was a platinum wire half a millimeter in diameter, cast a shadow on the fluorescent plate. The magnetic force H was established in the space between P and G by the current in the solenoid S. The deflection of the rays was measured by the displacement d of the shadow of the wire, and since d was small compared with the distance PG, the radius of curvature r of the trajectory was inversely proportional to d ($2rd = a^2$ approximately, a, being the distance PG).

Experiments made with a copper electrode at K gave the following results:

With air at different pressures, .03 to .07 millimeters. The potential W required to produce the discharge varied from 10630 volts to 3260 volts, but the quantity W/Hr remained constant, the mean value being proportional to 393, 398, 406, in a series of

experiments in which the cathode was placed at various distances from the wire P.

With coal-gas the mean value 401.5 was obtained in experiments in which W varied from 6410 to 11850 volts.

In hydrogen and carbonic acid the quantity $\sqrt{W}/Hr$ was found to be proportional to 404 and 398, the potential difference W ranging from 4000 to 14000 volts.

An aluminum cathode was also used with air in the tube, and the results were the same as those obtained with the copper electrodes.

Thus, the value of e/m is independent of the pressure, the distance between the electrodes, and the nature of the gas.

In order to obtain an exact value it was necessary to take into account the fact that the field is not absolutely uniform and to take accurate measurements of the force H along the line from P to G due to given current in the coil S.

When the rays traverse a distance x in the transverse magnetic field, the velocity v at right angles to the original direction of motion is:

$$v = \int_0^x He/m \, dx,$$

so that the small deflection d on a screen at a distance a from the origin is

$$\begin{aligned} d &= \int_0^a v dt \\ &= e/mv \int_0^a dx \int_0^x H dx \\ &= \sqrt{e/2mW} \int_0^a dx \int_0^x H dx. \end{aligned}$$

Later, Kaufman made a complete investigation of the magnetic

field and found the value of e/m for cathode rays to be 1.77×10^7.

Simon, working with the same apparatus as Kaufmann, with some improvements, found the value of e/m to be 1.865×10^7.

<u>Thomson's Methods</u>.- Sir J.J. Thomson, in 1897, determined e/m by two different and independent methods; and his values are in general agreement with those obtained by Kaufmann and Wiechert.

(a) First Method.- He considered a bundle of homogeneous cathode rays, m being the mass of each of the particles, e the charge, N the number of particles passing across any section of the beam in a given time; then Q the quantity of electricity carried by these particles is given by the equation:

$$Ne = Q.$$

When these rays strike against a solid body the temperature of the body is raised; the kinetic energy of the moving particles being converted into heat. If we suppose that all this energy is converted into heat, then, if we measure the increase in the temperature of a body of known thermal capacity caused by the impact of these rays, we can determine W, the kinetic energy of the particle, and if u is the velocity of the particles,

$$1/2Nmv^2 = W.$$

If r is the radius of curvature of the path of these rays in a uniform magnetic field H, then

$$mv/e = Hr = I$$

where I is written for Hr for the sake of brevity. From these equations we get

$$1/2v^2\ m/e = W/Q$$

$$v = 2W/QI$$

therefore $$m/e = I^2Q/2W.$$

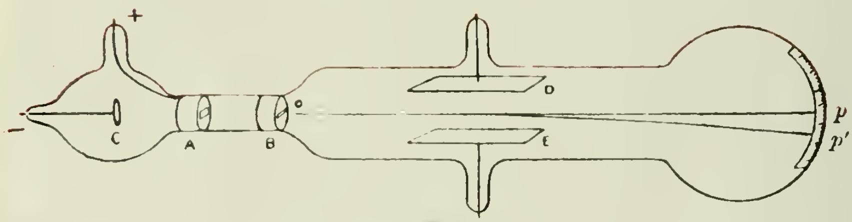
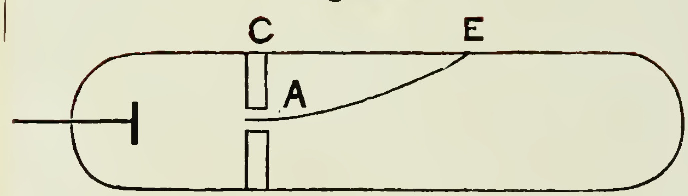


Fig. 3 .

If we know Q, W and I, we can deduce the value of e/m.

Thomson used tubes of three different types; the first one is represented in Fig.3, except that the plates E and D were absent. Two coaxial plates are fastened to the ends of the tube. The rays from the cathode C fall on the metal plug B, which is connected with the earth, and serves for the anode. A horizontal slit is cut in the plug B. The cathode rays pass through this slit and then strike against the two co-axial cylinders at the end of the tube. Slits are cut in these cylinders, so that the cathode rays pass into the inside of the inner cylinder. The outer cylinder is connected with the earth. The inner cylinder which is insulated from the outer one, is connected with an electrometer, the deflection of which measures the quantity of electricity Q brought into the inner cylinder by the rays. A thermo-electric couple is placed behind the slit in the inner cylinder. This couple is made of very thin strips of iron and copper fastened to very fine iron wires. These wires passed through the cylinders, being insulated from them, and through the glass to the outside of the tube, where they were connected with a low resistance galvanometer. The deflection of which gave data for calculating the rise of temperature of the junction produced by the impact against it by the cathode rays. The strips of iron and copper were large enough to insure that every cathode ray which entered the inner cylinder struck against the junction. In some of the tubes the strips of iron and copper were placed end to end, so that some of the rays struck against the iron and others against the copper. In others the strip of one metal was placed in front of the other. No difference, however, could be detected between the results gotten with these two arrangements. The strips of iron and copper were weighed,

Fig. 4.



and the thermal capacity in one set of junction was 5×10^{-3} microfarad, and in the other 3×10^{-3}. If we assume that the cathode rays which strike against the junctions give their energy up to it, the deflection of the galvanometer gives us W or $1/2Nmv^2$.

The value of I, i.e., Hr, where r is the curvature of the path of the rays in a magnetic field of strength H, was found as follows:

The tube was fixed between two large circular coils placed parallel to each other, and separated by a distance equal to the radius of either. These coils produced a uniform magnetic field, the strength of which is gotten by measuring with an ammeter the strength of the current passing them. The cathode rays are thus in a uniform field, so that their path is circular. Suppose that the rays when deflected by a magnet strike against the glass of the tube at E as shown in Fig.4. Then, if r is the radius of circular path of the rays,

$$2r = \frac{CE^2}{AC} + AC.$$

Then if we measure CE and AC we have the means of determining the radius of curvature of the path of the rays.

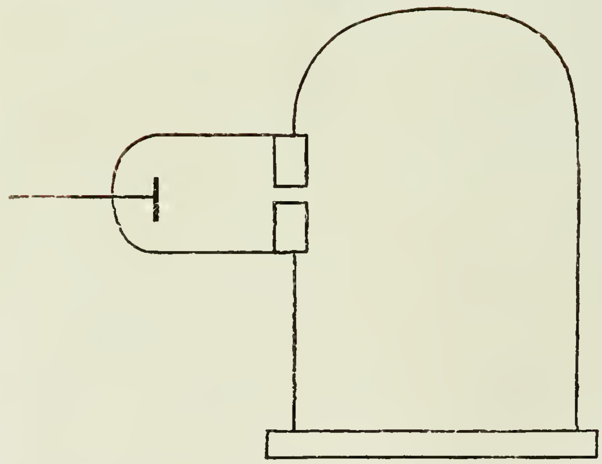
The determination of r is rendered to some extent uncertain, in consequence of the pencil of rays spreading out under the action of the magnetic field so that the phosphorescent patch at e is several millimeters long. Thus values of r differing appreciably from each other will be gotten by taking E at different points of this phosphorescent patch. Part of this patch was, however, generally considerably brighter than the rest. When this was the case, E was taken as the brightest point. When such a point of maximum brightness did not exist the middle of the patch was taken for E. The

uncertainty in the value of r thus introduced amounted sometimes to about 20 per cent. By this it is meant that if we take E first at one extremity of the patch and then at the other, we should get values of r differing by this amount.

The measurement of Q, the quantity of electricity which enters the inner cylinder, is complicated by cathode rays, making the gas through which they pass a conductor, so that though the insulation of the inner cylinder was perfect when the rays were off, it was not so when they were passing through the space between the cylinders. This caused some of the charge communicated to the inner cylinder to leak away, so that the actual charge given to the cylinder by the cathode rays was larger than that indicated by the electrometer. To make the error from this cause as small as possible, the inner cylinder was connected to the largest capacity available, 1.5 microfarads, and the rays were only kept on for a short time, about one or two seconds, so that the alteration in potential of the inner cylinder was not large, ranging in the various experiments from about .5 to 5 volts. Another reason why it is necessary to limit the duration of the rays to as short a time as possible, is to avoid the correction for the loss of heat from the thermo-electric junction by conduction along the wires. The rise in temperature of the junction by conduction was of the order 2°C. A series of experiments showed that with the same tube and the same gaseous pressure, Q and W were proportional to each other when the rays were not kept on too long.

Tubes of this kind gave satisfactory results. The chief drawback being that sometimes in consequence of the charging of the glass walls of the tube, a secondary discharge started from the cylinder to the walls of the tube, and the cylinders were surrounded

Fig. 5.



by a glow. When this glow appeared, the readings were very irregular. The glow could, however, be gotten rid of by pumping and letting the tube rest for some time. The results gotten with this tube by Sir. J.J. Thomson are given in Table I.

The second type of tube was like the one shown in Fig.5. A double cylinder with a thermo-electric junction like those used in the previous tube were placed in the line of fire of the rays. The inside of the bell jar was lined with copper gauge connected with the earth. This tube gave very satisfactory results. There never appeared any glow around the cylinders, and the readings were more concordant. The only drawback was that some of the connections had to be made with sealing wax, and hence it was not possible to get the highest exhaustion with this tube so that the range of pressure was less than that for tube No.1. The results gotten with this tube are given in Table II.

The third type of tube used by Sir J.J. Thomson was similar to the first one except that the openings in the two cylinders were made very much smaller. In this tube the slits in the cylinders were replaced by small holes about 1.5 millimeters in diameter. In consequence of the smallness of the openings the magnitude of the effect was very much reduced. In order to get measureable results, it was necessary to reduce the capacity of the condenser in connection with the inner cylinder to .15 microfarad, and to make the galvanometer exceedingly sensitive, as the rise in temperature of the thermo-electric junction was in these experiments only about .5°C on the average. The results obtained in this tube are given in Table III.

It will be noticed that the value of m/e is greater,

TABLE I

Gas	Value of W/Q	I	m/e	e/m	v
air	4.6×10^{11}	230	$.57 \times 10^{-7}$	1.75×10^{7}	4.0×10^{9}
air	1.8×10^{12}	350	$.34 \times 10^{-7}$	2.94×10^{7}	1.0×10^{10}
air	6.1×10^{11}	230	$.43 \times 10^{-7}$	2.33×10^{7}	5.4×10^{9}
air	2.5×10^{12}	400	$.32 \times 10^{-7}$	3.12×10^{7}	1.2×10^{10}
air	5.5×10^{11}	230	$.48 \times 10^{-7}$	2.08×10^{7}	4.8×10^{9}
air	1.0×10^{12}	285	$.40 \times 10^{-7}$	2.5×10^{7}	7.0×10^{9}
air	1.0×10^{12}	285	$.40 \times 10^{-7}$	2.5×10^{7}	7.0×10^{9}
hydrogen	6.0×10^{12}	205	$.35 \times 10^{-7}$	2.86×10^{7}	6.0×10^{9}
hydrogen	2.1×10^{12}	460	$.50 \times 10^{-7}$	2.0×10^{7}	9.2×10^{9}
carbonic acid	8.4×10^{11}	260	$.40 \times 10^{-7}$	2.5×10^{7}	7.5×10^{9}
carbonic acid	1.47×10^{12}	340	$.40 \times 10^{-7}$	2.5×10^{7}	8.5×10^{9}
carbonic acid	3.0×10^{12}	480	$.39 \times 10^{-7}$	2.57×10^{7}	1.3×10^{10}

TABLE II

gas	value of W/Q	I	m/e	e/m	v
air	2.8×10^{11}	175	$.53 \times 10^{-7}$	1.89×10^{7}	3.3×10^{9}
air	4.4×10^{11}	195	$.47 \times 10^{-7}$	2.13×10^{7}	4.1×10^{9}
air	3.5×10^{11}	181	$.47 \times 10^{-7}$	2.13×10^{7}	3.8×10^{9}
hydrogen	2.8×10^{11}	175	$.53 \times 10^{-7}$	1.89×10^{7}	3.3×10^{9}
air	2.5×10^{11}	160	$.51 \times 10^{-7}$	1.96×10^{7}	3.1×10^{9}
carbonic acid	2.0×10^{11}	148	$.54 \times 10^{-7}$	1.85×10^{7}	2.5×10^{9}
air	1.8×10^{11}	151	$.63 \times 10^{-7}$	1.59×10^{7}	2.3×10^{9}
hydrogen	2.8×10^{11}	175	$.53 \times 10^{-7}$	1.89×10^{7}	3.3×10^{9}
hydrogen	4.4×10^{11}	201	$.46 \times 10^{-7}$	2.18×10^{7}	4.4×10^{9}
air	2.5×10^{11}	176	$.61 \times 10^{-7}$	1.64×10^{7}	2.8×10^{9}
air	4.2×10^{11}	200	$.48 \times 10^{-7}$	2.08×10^{7}	4.1×10^{9}

TABLE III

gas	value of W/Q	I	m/e	e/m	v
air	2.5×10^{11}	220	$.90 \times 10^{-7}$	1.11×10^{7}	2.4×10^{9}
air	3.5×10^{11}	225	$.70 \times 10^{-7}$	1.43×10^{7}	3.2×10^{9}
hydrogen	3.0×10^{11}	250	1.00×10^{-7}	1.00×10^{7}	2.5×10^{9}

considerably, for tube No.3 than for Tubes No.1 and 2. In tube No.3 the opening is a small hole and in No.1 and 2 it is a slit of much greater area. The values of m/e gotten from tube No.1 and 2 are too small, in consequence of leakage from the inner to the outer cylinder by the gas being rendered a conductor by the passage of the cathode rays.

It will also be noticed that the value of m/e is independent of the nature of the gas. Thus, for the first tube the mean for the air is $.4 \times 10^{-7}$, for hydrogen, $.42 \times 10^{-7}$, and for carbonic acid gas $.4 \times 10^{-7}$.

For the second tube the mean value of m/e for air is $.52 \times 10^{-7}$, for hydrogen $.50 \times 10^{-7}$, and for carbonic acid gas $.54 \times 10^{-7}$.

(b) Second Method of Sir J.J. Thomson.- This method is based upon the simultaneous deflection of cathode rays in an electrostatic field and in a magnetic field. If the deflection experienced by the rays when traversing a given length under a uniform electric intensity, and the deflection of the rays when they traverse a given distance under a uniform magnetic field, are measured, the values of e/m and $\underline{v}$ can be found in the following way:

Let the space passed over by the rays under a uniform electric intensity $\underline{F}$ be $\underline{l}$, the time taken by the rays to traverse this space is l/v, the velocity in the direction of $\underline{F}$ is therefore

$$\frac{Fe}{m} \cdot \frac{l}{v}$$

so that θ, the angle through which the rays are deflected when they leave the electric field and enter a region free from electric force is given by the equation

$$\theta = \frac{Fe}{m} \cdot \frac{l}{v^2} \cdot$$

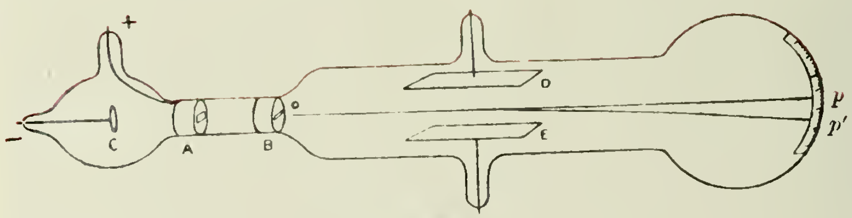


Fig. 6 .

If, instead of the electric intensity, the rays are acted on by a magnetic force H at right angles to the rays, and extending across the distance l, the velocity at right angles to the original path of the rays is $\frac{Hev}{m} \cdot \frac{l}{v}$, so that ϕ, the angle through which the rays are deflected when they leave the magnetic field, is given by the equation

$$\phi = \frac{He}{m} \cdot \frac{l}{v} \cdot$$

From these equations we get

$$v = \frac{\phi}{\theta} \cdot \frac{F}{H}$$

and

$$\frac{e}{m} = \frac{\phi^2}{\theta} \cdot \frac{F}{H^2} \cdot \frac{1}{l} \cdot$$

In the actual experiment H is adjusted so that $\theta = \phi$. In this case the equation becomes

$$v = \frac{F}{H}$$

and

$$\frac{e}{m} = \frac{F\theta}{H^2 l} \cdot$$

The apparatus used in this experiment is represented in Fig. 6. The electric field is produced by connecting the two aluminum plates to the terminals of a battery of storage cells. The phosphorescent patch at the end of the tube is deflected and the deflection measured by a scale pasted on the end of the tube. As it was necessary to darken the room to see the phosphorescent patch, a needle coated with luminous paint was placed so that by a screw it could be moved up and down the scale. This needle could be seen when the room was darkened, and it was moved until it coincided with the phosphorescent patch. Thus, when light was admitted the deflection on the phosphorescent patch could be measured.

The magnetic field is produced by placing outside the tube two coils whose diameter is equal to the length of the plates. The coils are so placed so that they cover the space occupied by the plates. The distance between the coils is equal to the radius of either. The mean value of the magnetic force over the length is determined in the following way:

A narrow coil C whose length is 1, connected with a ballistic galvanometer, is placed between the coils. The plane of the windings of C is parallel to the planes of the coils. The cross-section of the coil is a rectangle 5 cm. by 1 cm., With a given current sent through the outer coils, the kick of the galvanometer is observed when this current is reversed. The coil C is then placed at the center of the two very large coils, so as to be in a field of uniform magnetic force. The current through the large coil is reversed and the kick of the galvanometer is again observed. By comparing both kicks, first one called α, and the second one β, the mean value of the magnetic force over a length 1 is gotten. This was found by Sir J.J. Thomson to be 60 x i where i is the current flowing through the coils. Thomson made a series of experiments to see if the electrostatic deflection was proportional to the electric intensity between the plates. This was found to be the case.

The results obtained by Thomson are given in the following table. He adjusted the current through the coils so that the electrostatic deflection was the same as the magnetic.

gas	θ	H	F	l	m/e	e/m	v
air	8/110	5.5	1.5×10^{10}	5	1.3×10^{-7}	$.77 \times 10^{7}$	2.8×10^{9}
air	9.5/110	5.4	1.5	5	1.1	.91	2.8
air	13/110	6.6	1.5	5	1.2	.83	2.3
hydrogen	9/110	6.3	1.5	5	1.5	.67	2.5
carbonic acid	11/110	6.9	1.5	5	1.5	.67	2.2
air	6/110	5.0	1.8	5	1.3	.77	2.6
air	7/110	3.6	1.0	5	1.1	.91	2.8

The cathode in the first five experiments was aluminum. In the last two experiments it was made of platinum. In the last experiment Sir William Crookes' method of getting rid of the mercury vapor by inserting tubes of pounded sulphur, sulphur iodide and copper filings between the bulb and the pump was adopted. In the calculation of e/m and v, no allowance has been made for the magnetic force due to the coil in the region outside the plates. In this region the magnetic force will be in the opposite direction to that between the plates, and will tend to bend the cathode rays in the opposite direction. Thus the effective value of H will be smaller than the value used in the equations so that the values of m/e are larger and those of v much less than they would be if this correction is applied.

It will be seen from these determinations that the value of m/e is independent of the nature of the gas, and that its value, 10^{-7}, is very large as compared with the value 10^{-4}, which is the largest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis.

The same method as described above has been used a number

of times in the laboratory of physics at the University of Illinois, by Professor C.T. Knipp. The following results were obtained by three members of the graduating class of 1921, under his supervision.

TABLE IV *

Time	PD	I	I^2	y	z	z^2	v	e/m	p
2.25	328.0	.183	.0335	1.25	1.75	6.06	3.10×10^9	1.97×10^7	.00692
2.32	327.6	.180	.0324	1.275	1.80	3.24	3.01×10^9	1.75×10^7	.0078
2.39	327.2	.181	.0326	1.325	1.85	3.41	2.96×10^9	1.75×10^7	.0088
2.46	326.8	.175	.0306	1.42	1.90	3.61	2.93×10^9	1.82×10^7	.00988
2.53	326.4	.182	.0331	1.50	2.00	4.00	2.80×10^9	1.68×10^7	.0106
3.00	326.0	.182	.0331	1.50	2.05	4.2	2.81×10^9	1.69×10^7	.01116
3.07	325.6	.182	.0331	1.55	2.10	4.41	2.85×10^9	1.70×10^7	.0118
3.14	325.3	.183	.0335	1.56	2.15	4.61	2.89×10^9	1.89×10^7	.01204
3.21	325.0	.183	.0335	1.60	2.20	4.84	2.88×10^9	1.87×10^7	.01268
3.28	324.6	.180	.0324	1.60	2.20	4.84	2.93×10^9	1.98×10^7	.01312
3.35	324.3	.180	.0324	1.62	2.2	4.84	2.91×10^9	1.90×10^7	.01380
3.42	324.0	.176	.0310	1.725	2.2	4.84	2.78×10^9	1.87×10^7	.01428
3.49	323.5	.175	.0306	1.75	2.2	4.84	2.75×10^9	1.80×10^7	.01476
3.56	323.3	.181	.0326	1.80	2.2	4.84	2.58×10^9	1.71×10^7	.01508
4.03		.175	.0306	1.85	2.15	4.61	2.54×10^9	1.69×10^7	.01508
				Another set of data taken on a different date.					
2.05	324.	.187	.035	1.05	1.70	2.89	3.30×10^9	1.74×10^7	.0040
2.15	322.8	.1865	.0347	1.18	1.80	3.24	2.95×10^9	1.75×10^7	.0067
2.25	321.6	.1865	.0347	1.35	1.875	3.52	2.82×10^9	1.66×10^7	.0085
2.35	320.4	.1865	.0347	1.45	1.90	3.61	2.67×10^9	1.77×10^7	.0100
2.45	319.2	.1865	.0347	1.55	2.00	4.00	2.62×10^9	1.85×10^7	.0112
2.55	317.	.1865	.0347	1.60	2.05	4.20	2.51×10^9	1.67×10^7	.0116

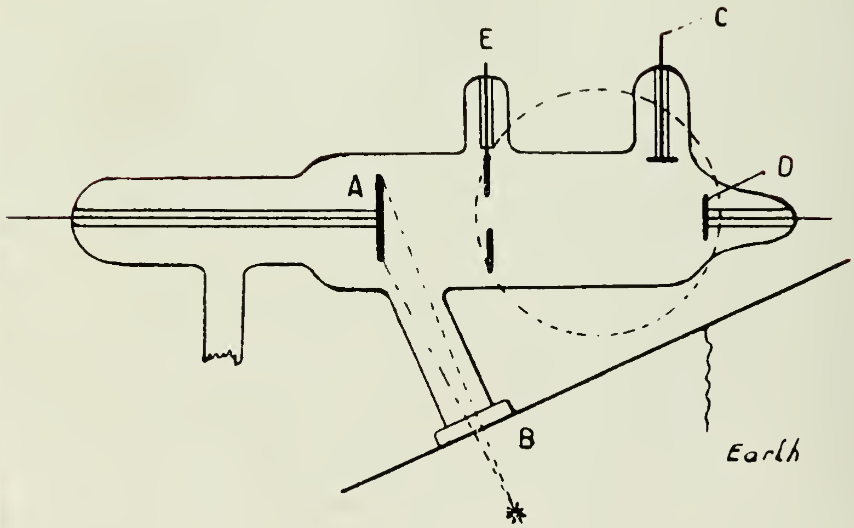


Fig. 7 .

While in the process of taking this data something went wrong and so after waiting a short time a new set of data was taken. The same is given below:

Time	PD	I	I^2	y	z	z^2	v	e/m	9
3.25	317.	.1865	.0347	.90	1.65	2.72	3.72×10^9	1.91×10^7	.0048
3.35	317.	.1865	.0347	1.05	1.70	2.89	3.29×10^9	1.81×10^7	.0050
3.45	317.	.1865	.0347	1.10	1.75	3.06	3.09×10^9	1.77×10^7	.0056
3.55	317.	.1865	.0347	1.15	1.80	3.24	3.12×10^9	1.75×10^7	.0071
4.05	317.	.1865	.0347	1.20	1.85	3.41	3.06×10^9	1.775×10^7	.0081

III. DETERMINATION OF e/m FOR PARTICLES SET FREE BY ULTRA VIOLET LIGHT, AND FOR THE NEGATIVELY CHARGED PARTICLES EMITTED BY INCANDESCENT SOLIDS

(a) Lenard's Method.- The earlier investigations of the negatively charged particles obtained by different methods in gases at low pressures show that the ratio e/m was probably exactly the same in all cases. Lenard in 1900, using a similar method to that of Kaufmann, determined the ratio of the charge to the mass of a particle set free by the action of the Ultra-violet light from a metal surface, and obtained the number 1.15×10^7. His apparatus is shown in Fig.7.

A is an aluminum plate on which the ultra-violet light shines. This light comes from a spark between zinc electrodes and enters the tube through the quartz window, B. E is another metal electrode perforated in the middle and connected with the earth. It shields the right hand apparatus from the electrostatic action of

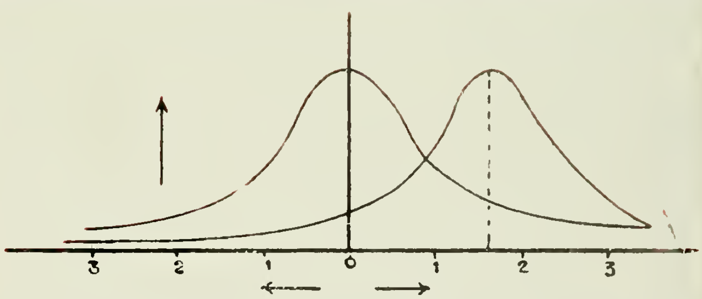


Fig. 8

the charged electrode, A. D and C are electrodes which can be connected with an electrometer. When A is charged up a stream of negative electricity goes through the opening in E and, striking against the plate D, charges up the electrometer with negative electricity. If the electrometer be connected with C instead of with D, it will not receive any charge. A charge, however, can be given to C by deflecting the stream of negative ions by means of a magnet until they strike against C. As we still further increase the magnetic field, the ions will be deflected by the field past C, and the charge communicated to C will fall off rapidly. The amount of negative electricity received by the electrodes D and C respectively, as the magnetic force is increased, was in Lenard's experiments represented by the curves in Fig. 8. The ordinates are the charges received by the electrodes and the abscissae are the values of the magnetic force. The curve to the left is for the electrode D, that to the right for C. Since the negative ions are not exposed to any electric field in the part of the tube to the right of E, their paths in this region under a constant negative field will be circles whose radii are equal to mv/eH. C will receive the minimum charge when the circle with this radius passing through the middle of the hole in E, and having its tangent horizontal at this point, passes also through the middle of the electrode C. The radius R of this circle is fixed by the relative positions of E and C. Hence, if we measure H when C receives its maximum charge, we have

$$R = mv/eH. \tag{1}$$

Reiger found for the negative ions emitted by glass when exposed to ultra-violet light, values of e/m ranging from 9.6×10 to 1.2×10^7.

(b) Sir J.J. Thomson's Method.- Elster and Geitel have shown that the rate of escape of negative electrification at low pressure is much diminished by magnetic force if the lines of magnetic force are at right angles to the lines of electric force. Let us consider what effect a magnetic force would have on the motion of a negatively electrified particle. Let the electric force be uniform and parallel to the axis of x, while the magnetic force is also uniform and parallel to the axis of z. Let the pressure be so low that the mean free path of the particles is long as compared with the distance they move while under observation, so that we may leave out of account the effect of collisions on the movements of the particles.

If m is the mass of a particle, e its charge, X the electric force, H the magnetic force, the equations of motion are:

$$\frac{md^2x}{dt^2} = Xe - He\frac{dy}{dt}$$

and

$$\frac{md^2y}{dt^2} = He\frac{dx}{dt}\cdot$$

Eliminating x we have

$$m\,\frac{d^3y}{d't^3} = \frac{He}{m}\,(Xe-He\,\frac{dy}{dt}).$$

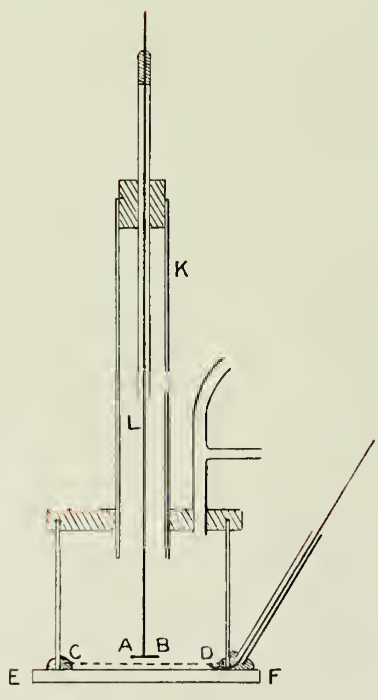
The solution of these equations if x,y, dx/dt, dy/dt all vanish when t is zero, is expressed by

$$y = \frac{Xm}{eH^2}\left(Ht\,\frac{e}{m} - \sin\frac{Hte}{m}\right)$$

$$x = \frac{Xm}{eH^2}\left(1-\cos\frac{Hte}{m}\right)$$

The equations show that the path of the particles is a cycloid, the generating circle of which has a diameter equal to $\frac{2Xm}{eH^2}$, and rolls on the line X = 0.

Fig. 9.



Suppose now that we have a metal plate AB exposed to ultra violet light, placed parallel to a large metal plate CD perforated so as to allow the light to pass through it and fall upon the plate AB. See Fig.9. Then if CD is at a higher electric potential than AB, the particles travel along the lines of electric force. Let us now suppose that a uniform magnetic force equal to H and at right angles to the electric force acts on the particles. These particles will now describe a cycloid and will reach a distance $\frac{2Xm}{eH^2}$. Every particle which leaves AB will reach CD provided CD stretches forward enough to prevent the particles passing by on one side. Now, the distance parallel to y through which the particles have travelled when it is at the greatest distance from AB is $\frac{\pi Xm}{eH^2}$. Hence, if CD stretches beyond AB by this distance at least, all the particles will be caught by CD and the magnetic field will produce no diminution in the rate of leak between AB and CD. If, on the other hand, the distance between the plates is greater than $\frac{2Xm}{eH^2}$, then a particle starting from AB will turn back before it reaches CD. It will thus never reach it, and the rate at which CD acquires negative electrification will be diminished by the magnetic force. Hence, if this view of the action of the magnetic field is correct, and if we begin with the plates very near together, and gradually increase the distance between them, we should expect that, at first with the plates quite close together, the rate at which CD received a negative charge would not be effected by the magnetic force, but as soon as the distance between the plates is equal to $\frac{2Xm}{eH^2}$ the magnetic force will greatly diminish the rate at which CD receives a negative charge, and will in fact reduce the rate almost to zero if all the negatively electrified particles came from the surface of AB. Hence, if we

measure the distance between the plates when the magnetic force first diminishes the rate at which CD receives a negative charge, we shall determine the value of $\frac{2Xm}{eH^2}$; and we can easily determine X and H, and from them the value of e/m can be deduced.

In the apparatus shown, AB is a carefully polished zinc plate about one centimeter in diameter; while CD is a grating composed of very fine wires crossing each other at right angles, the ends being soldered into a ring of metal. The wires form network with a mesh about one millimeter square. This is placed parallel to AB on the quartz plate EF which is about four millimeters thick. The grating was very carefully insulated. The system is enclosed in a glass tube which is connected with a mercury pump provided with a McLeod gauge. The ultra violet light is supplied from an arc about three millimeters long between zinc terminals. The induction coil giving the arc is placed in a metal box, and the light is placed through a window cut in the top of the box. Over this window the quartz base of the vessel is placed. A piece of wire gauze connected with the earth is placed between the quarts and the window. The plate AB is carried by the handle L which passes through a sealing-wax stopper in the tube K. The magnet used is an electromagnet of the horse shoe type. The magnetic force due to magnet is determined by observing the deflection of a ballistic galvanometer when an exploring coil, of approximately the same vertical dimensions as the distance between the plates AB and CD was withdrawn from between its poles. The coil is carefully placed so as to occupy the same part of the magnetic field as that occupied by the space between AB and CD when the magnet was used to affect the rate of leak of electricity between AB and CD. In this way the intensity of the magnetic field between the poles of the magnet was determined

by Thomson for a series of values of the current through the magnetizing coils of the electromagnet ranging between 1 and 4.5 amperes, and a curve was drawn which gave the magnetic force when the magnetizing current read by an ammeter was known.

The pressure of the gas in the tube containing the plate is reduced by the mercury pump to 1/100 of a millimeter of mercury. The rate of leak of negative electricity to CD when AB was exposed to ultra-violet light is measured by an electrometer. The zinc plate is connected with the negative pole of a battery of small storage cells. The positive pole of which is put to earth. One pair of the quadrants of the electrometer is kept permanently connected with the earth. The other pair is connected with the wire gauze CD. Initially the two pairs of the quadrant are connected together; the connection is then broken and the ultra-violet light is allowed to fall on the zinc plate. The negative charge received by the wire gauze in a given time is proportional to the deflection of the electrometer in that time. By this method the following results were obtained by Thomson, When the difference of potential between the illuminated plate and the wire gauze was greater than a certain value depending upon the intensity of the magnetic force, and the distance between AB and CD, no diminution in the deflection of the electrometer was produced by the magnetic field. In fact in some cases the deflection was just a little greater in the magnetic field.

The negative ions travelling between the plates will disturb, to some extent, the uniformity of the field between the plates. But if the intensity of the ultra-violet light is not too great, so that the rate of the leakage and the number of ions between the plates is not large, this want of uniformity will not be important.

Following is a specimen of observations:

Distance between the plates	.29 centimeters
Strength of the magnetic field	164 units
Pressure	1/100 millimeter

P.D. between poles in volts	Deflection of electrometer in 30 seconds	
	Magnet off	Magnet on
240	180	190
120	160	165
80	160	140
40	130	75

These observations showed that the critical value of the potential difference was about 80 volts. A series of observations was then made with potential difference increasing from 80 volts by two volts at a time, and it was found that 90 volts was the largest potential difference at which any effect due to the magnet could be detected. The results of a number of experiments are given in the following table:

d (in cm.)	H	V (in absolute measurement)	e/m
.18	170	40×10^8	8.5×10^6
.19	170	30×10^8	5.8×10^6
.20	181	46×10^8	7.1×10^6
.29	167	84×10^8	7.1×10^6
.29	164	90×10^8	7.6×10^6
.30	160	86×10^8	7.4×10^6
.45	100	80×10^8	7.9×10^6

The mean value for e/m is 7.3×10^6.

The value of e/m in case of the convection of electricity under the influence of ultra-violet light is of the same order as in the case of the cathode rays, and is very different from the value of e/m in the case of hydrogen ions in ordinary electrolysis which is equal to 10^4. The value, e, is the same, hence the mass must be different and is of the order of 1/1000 of hydrogen ion.

Thomson conducted experiments on the determination of e/m for the negative ion produced by an incandescent wire. His method was the same as described above in case of ultra-violet light falling on a plate. He found the value of e/m to be 8.7×10^6.

Owen determined the value of e/m for the particles emitted by a glowing Nernst filament. He found the value to be 5.65×10^6 and for those emitted by glowing lime Wehnelt found the value of e/m to be 1.4×10^7.

IV. M. and MADAME CURIE'S INVESTIGATIONS CONCERNING RADIOACTIVE SUBSTANCES

M. and Madame Curie had shown that the radioactive substance radium emits negative ions. Becquerel determined the velocity of these ions and the value of e/m. His method was based upon the deflection of the rays produced by an electrostatic and also by a magnetic field. The pressure was atmospheric, and the resistance offered to the motion of the ions by the gas through which they pass was neglected. The case cannot be justified but for ions emitted by radium, as they are very much more penetrating than those that have been hitherto considered, and are able to travel as far through a gas at atmospheric pressure as others at low pressure. So the value of v and e/m by this method would be right if the resistance of the

gas is neglected.

V. SUMMARY OF RESULTS

Careful investigations have been made of the ratio e/m and the results are in good agreement with the value 1.77×10^7 originally found by Kaufmann for cathode rays. The following are some of the recent determinations, e being expressed in electromagnetic units.

Slowly moving Becquerel rays, by magnetic and electrostatic deflection:

Kaufman	1.884×10^7	(1906)
Buchner	1.763×10^7	(1909)
Neumann	1.765×10^7	(1913)

Cathode Rays:

Bestelmeyer	1.72×10^7	(1907)	Magnetic and elec. defl.
Malassez	1.769×10^7	(1911)	" " " " between electrodes

Cathode Rays from glowing oxides, by magnetic deflection and potential difference between electrodes:

Classen,	1.776×10^7	(1908)
Bestelmeyer	1.766×10^7	(1911)

Photoelectric effect of magnetic deflection and potential difference between the electrodes:

Allusti 1.756×10^7 and 1.766×10^7 (1912)

Zeeman effect:

Weiss and Colton	1.767×10^7	(1907)
Stellenheimer	1.791×10^7	(1907)
Gmeliss	1.771×10^7	(1909)

TABLE OF VALUES OF e/m

Source of Ions	Observer	Date	Method of Determination	Value of e/m	$v \cdot 10^{-9}$
Cathode rays	J.J.Thomson	1897	Magnetic and electrostatic deflection	7.7×10^6	2.2-3.6
Cathode rays	J.J.Thomson	1897	Magnetic deflection and heating effect	1.17×10^7	2·4-3·2
Cathode rays	Kaufmann	1897-8	Magnetic deflection and potential difference	1.86×10^7	
Cathode rays	Simon	1899	Magnetic deflection and potential difference	1.865×10^7	
Cathode rays	Wiechert	1899	Magnetic deflection and velocity of ions	1.01×10^7 - 1.55×10^7	
Cathode rays	Seitz	1901	Magnetic and electrostatic deflection	6.45×10^6	7·03
Cathode rays	Seitz	1902	Magnetic and electrostatic deflection, heating effect and potential difference	1.87×10^7	5.7-7.5
Cathode rays	Starke	1903	Magnetic and electrostatic deflection	1.84×10^7	3.8-12
Cathode rays	Reiger	1905	Magnetic deflection and potential difference	1.32×10^7	
Cathode rays	Becker	1905	Magnetic deflection and retardation in electric field	1.8×10^7	10

Source of	Observer	Date	Method of Determination	Value of e/m	$v \cdot 10^{-9}$
Lenard rays	Lenard	1898	Magnetic and electrostatic deflection	6.39×10^6	
Lenard rays	Lenard	1898	Magnetic deflection and retardation in electric field	6.8×10^6	3.4-10
Ultra-violet light	J.J.Thomson	1899	Retardation of discharge by magnetic field	7.6×10^6	
Ultra-violet light	Lenard	1900	Magnetic deflection and potential difference	1.15×10^7	
Ultra-violet light	Reiger	1905	Magnetic deflection and potential difference	9.6×10^6 - 1.2×10^7	
Incandescent metals	J.J.Thomson	1899	Retardation of discharge by magnetic field	8.7×10^6	
Incandescent oxides	Owen	1904	Retardation of discharge by magnetic field	5.6×10^6	
Incandescent oxides	Wehnelt	1904	Magnetic deflection and potential difference	1.4×11^7	
Radium	Becquerel	1900	Magnetic and electrostatic deflection	10^7 approximately	2×10^{10}
Radium	Kaufmann	1901-2	Magnetic and electrostatic deflection	1.77×10^7 for small velocities	
Polonium	Ewers	1906	Magnetic and electrostatic deflection	1.7×10^7	

VI. CONCLUSIONS

If compared with the charge on a univalent ion in a liquid electrolyte the charge of the negative ion obtained in high vacua will be found to be the same. Charge is not effected by pressure so there is a good reason to believe that the charge is the same at all pressures.

The large value of e/m obtained for negative ion is due to the smallness of m which is less than the mass of an atom of hydrogen in the proportion 1:1830.

Kaufman investigated the ratio e/m at higher velocities approaching to that of light, and found that the value of e/m diminishes from the small velocity value to 1.31×10^{7}, when the velocity is 2.36×10^{10} and to $.63 \times 10^{7}$ when the velocity is 2.83×10^{10}.

This fact has an important bearing on electromagnetic theory. When an electric charge is in motion there is a certain amount of electromagnetic energy resident in the surrounding field, and the charge when accelerated exhibits the phenomena of inertia, even when supposed to devoid of ordinary mass.

When the velocity approaches that of light the mass of an electron increases, while for slow speeds the electromagnetic mass is in the order of e^2/a. e is the charge and a is the radius of the electron.

For acceleration in the direction of motion the charge behaves as though it had a mass m_l (longitudinal electromagnetic mass). While for acceleration at right angles to the direction of motion it appears to have a different mass m_t transverse electromagnetic mass).

Abraham and Lorentz in their theoretical investigations

have mentioned that the longitudinal mass is greater than the transverse mass. Abraham's theory considers the electron as rigid, and Lorentz's theory, for a special reason, considers it as contracting in the direction of the motion.

Lorentz's theory leads to the following formulae for m_l and m_t in terms of the velocity v of the particle.

$$m_l = m_o/(1-v^2/c^2)^{3/2}$$

$$m_t = m_o/(1-v^2/c^2)^{1/2}$$

both masses being equal to m when v is small compared with c the velocity of light.

This theory is justified since Kaufman's original determination of the transverse electromagnetic mass and the recent experiments of Bucheret with β rays, and those of Hupka on fast cathode rays, are in agreement with it.

All this supports the view that the mass of an electron is entirely electromagnetic.

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